Simulation of Acoustic Radiation from Turbulent Boundary Layers at High Mach Numbers

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NATO STO AVT-240 & RTG-082
Hypersonic Boundary-Layer Transition Prediction
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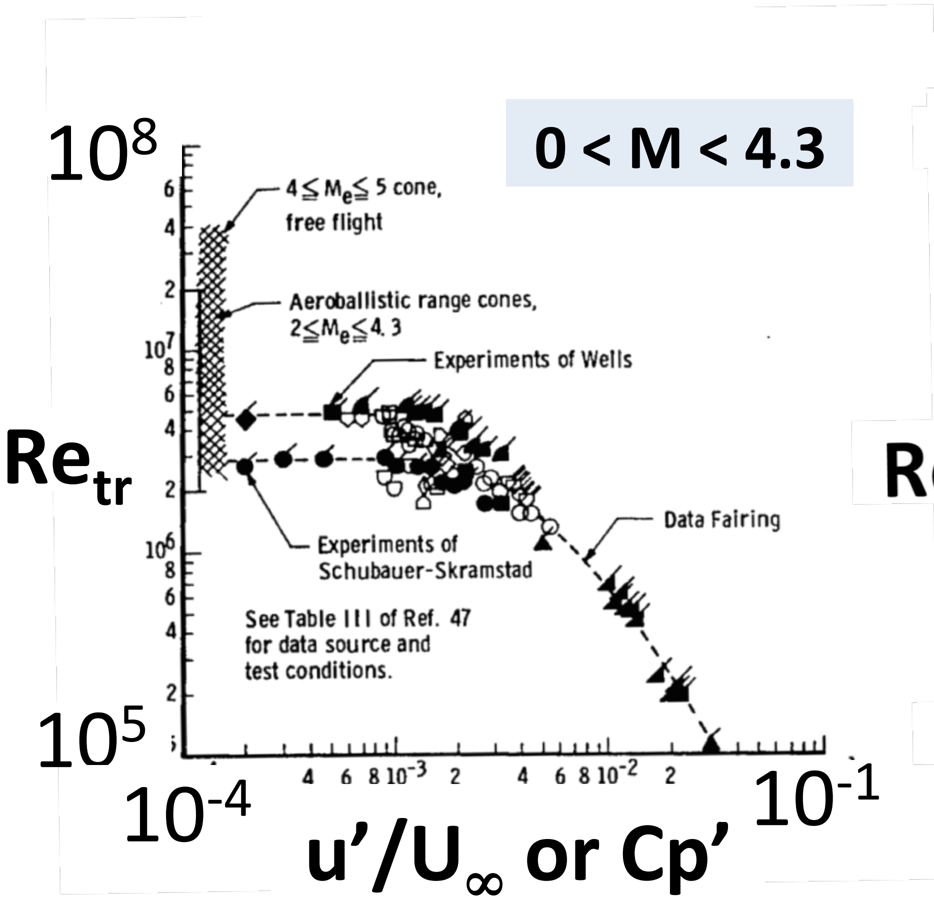
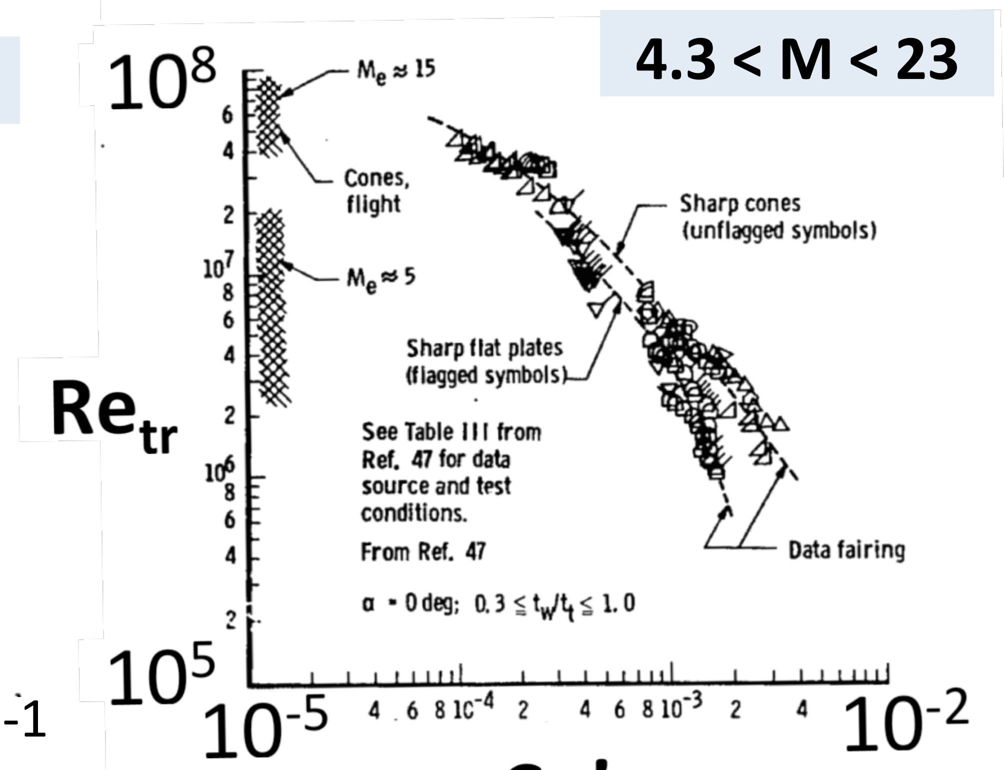
- Transition testing in hypersonic ground facilities
  - an important avenue to understanding the laminar-turbulent transition behavior of hypersonic vehicles
- Most hypersonic wind tunnels have elevated freestream disturbances
- **Tunnel Disturbances** have a large impact on Transition at M > 1

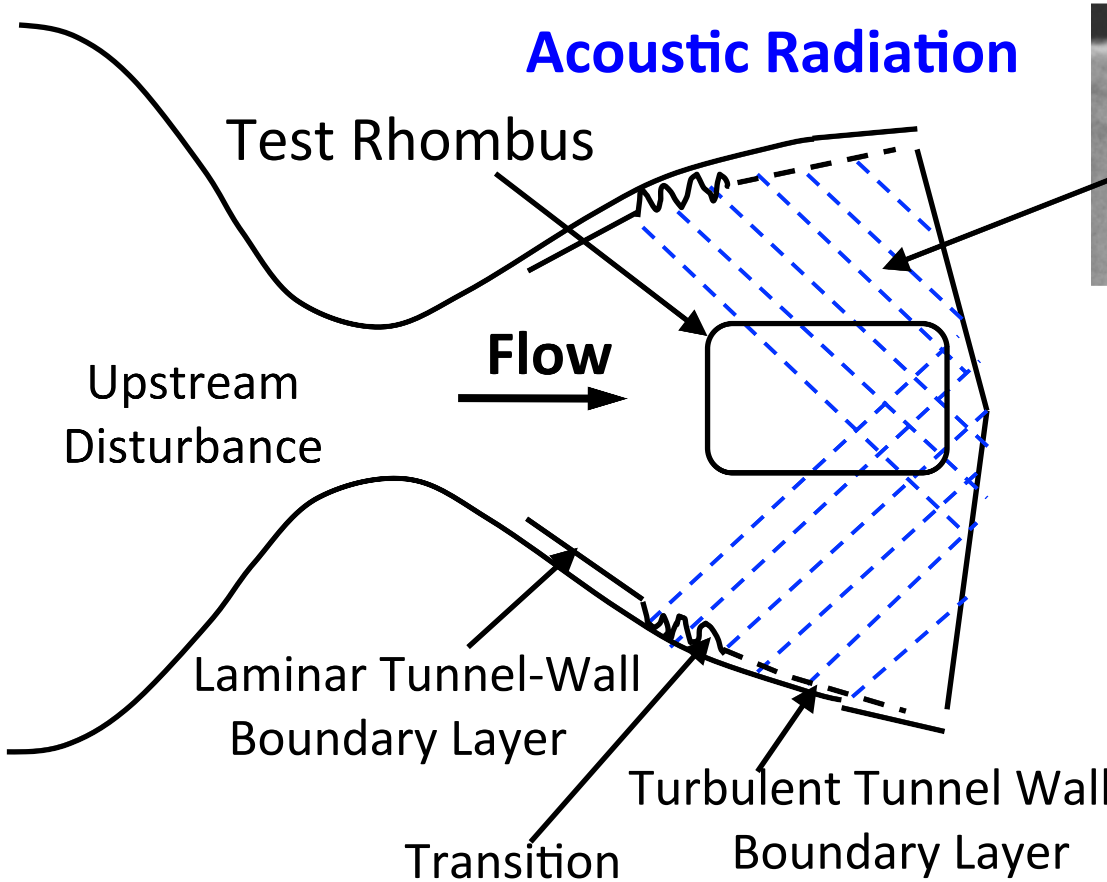


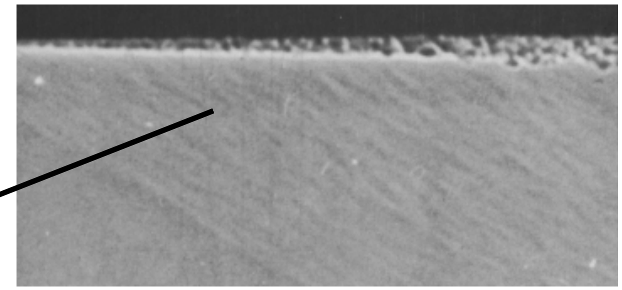


Harvey, 1978

Background

Disturbance Environment for Wind-Tunnel Facilities (Blanchard et al. 1997)





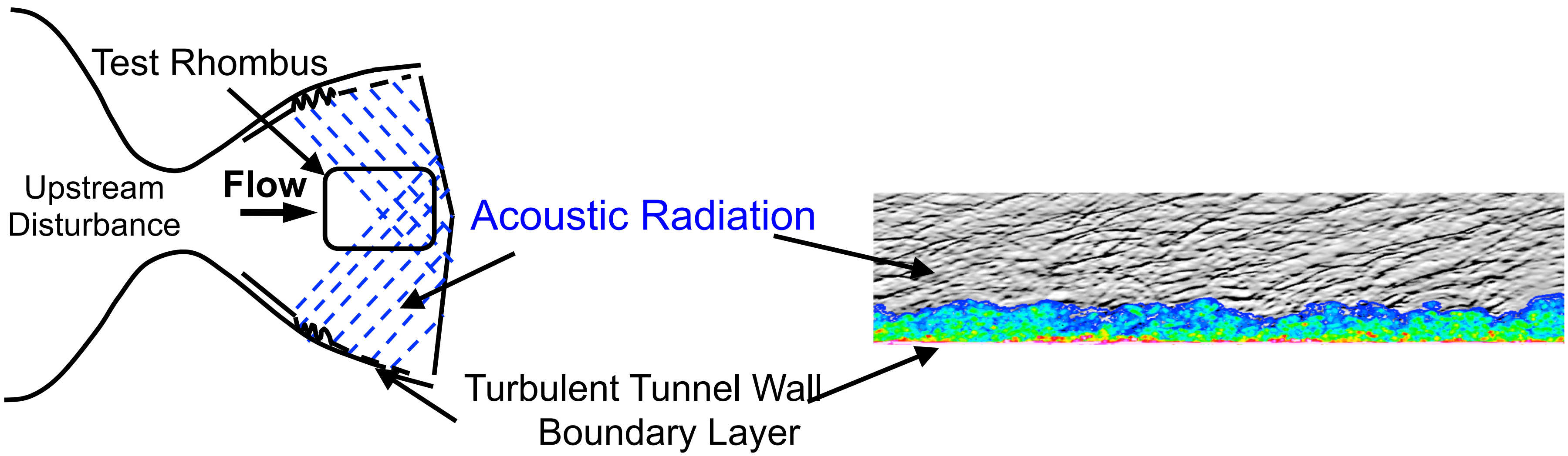
Shadowgraph of the radiated noise from a Mach 3.5 tunnel-wall turbulent boundary layer (courtesy of NASA Langley)

In a conventional ("noisy") tunnel, tunnel disturbances are dominated by acoustic radiation from tunnel wall turbulent boundary layers for M > 2.5 (Laufer, 1964)

Methodology

Approach

High-fidelity simulation of acoustic radiation from tunnel-wall turbulent boundary layers



Impact: Understanding the acoustic fluctuations in wind tunnels and their influence on boundary layer transition would enable

- Better use of transition data
- Meaningful application of receptivity theory (Fedorov and Khokhlov, 1991)
- Potential reconciliation of differences in transition onset across multiple facilities

Acoustic Radiation from High-Speed Turbulent BLs

Theory

- Eddy Mach wave convecting supersonically with respect to free stream (Phillips, 1960; Ffowcs-Williams & Maidanik 1963)
- Restricted to prediction of intensity of the freestream fluctuation

Experiments

- Laufer (1961, 1964); Kendall (1970); Rufer (2000); Bounitch et al. (2011); Masutti et al. (2013); Radespiel et al. (2013)
- Mostly limited to only amplitude, spectra with limited bandwidth; no multi-point statistics

Acoustic Radiation from High-Speed Turbulent BLS

Direct Numerical Simulations (*Duan et al., AIAA 2012-3070, AIAA 2013-0532, AIAA 2014-2912, JFM vol. 746, pp 165-192, 2014*)

- include both the flow field and near-acoustic field
- isolate a purely acoustic freestream disturbance field above a single tunnel wall
- Identify generic statistical and spectral features of freestream disturbances
- Open doors to further simulations of receptivity in a tunnel-like environment

DNS datasets:

- $M_\infty = 2.5$, $T_w/T_r = 1.0$, Flat Plate
- $M_\infty = 5.86$, $T_w/T_r = 0.76$, Flat Plate (M6Tw076) & $T_w/T_r = 0.25$, Flat Plate (M6Tw025)
  - Freestream condition representative of Purdue Quiet Tunnel under noisy condition with $p_0 = 132$ psi, $T_0 = 432$ K
- **$M_\infty = 14$, $T_w/T_r = 0.18$**, Flat Plate (preliminary analysis)
  - Freestream condition representative of AEDC Tunnel 9 at $p_0 = 1{,}023$ psi
  - Comparison with Boundary-layer measurements at AEDC Tunnel 9 (Expected)

Outline

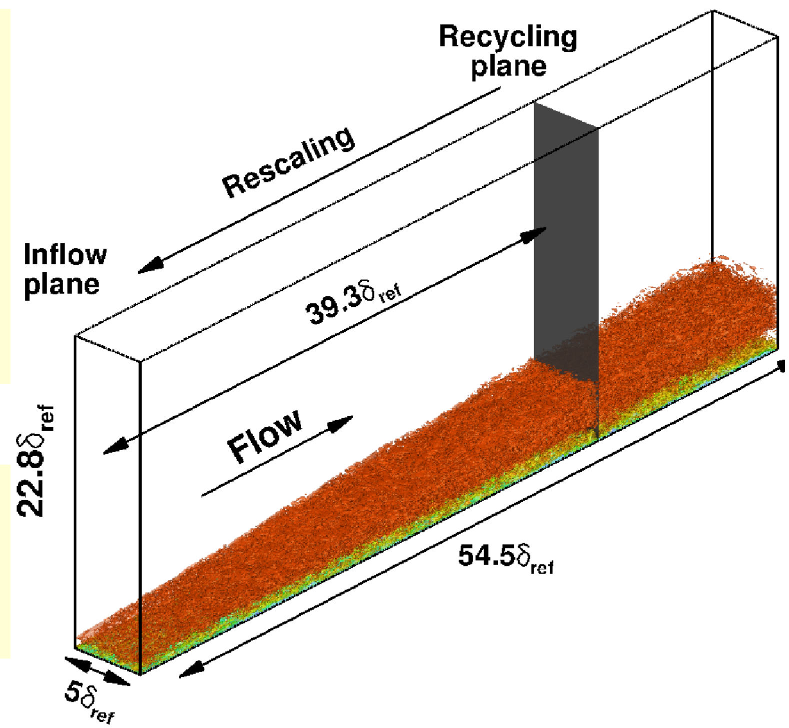
- DNS methodology
- Validation & Comparison with Experiments
- Effects of **freestream Mach number** and **wall cooling** on freestream p' fluctuations
  - Intensity
  - Frequency spectrum
  - Space-time correlation
  - Wave-front orientation
- Effect of geometric confinement on acoustic radiation
- Concluding remarks

DNS Setup
Case M14Tw18

- **WENO** *(Jiang & Shu 1996, Martin et al. 2007)*

- Uniform grid in streamwise-spanwise directions
  - $\Delta x^+ \approx 9.9$, $\Delta y^+ \approx 4.9$
- $\Delta z_w^+ \approx 0.5$, $N_z = 19$ for $z^+ < 10$,
- $\Delta z_\delta^+ \approx 5.2$, $N_z = 186$ for $z < \delta$
- $N_x \times N_y \times N_z = 2500 \times 460 \times 540$ (Total: 621 M)

- Grids designed to simultaneously resolve both the **hydrodynamic disturbances** and **near-acoustic field**



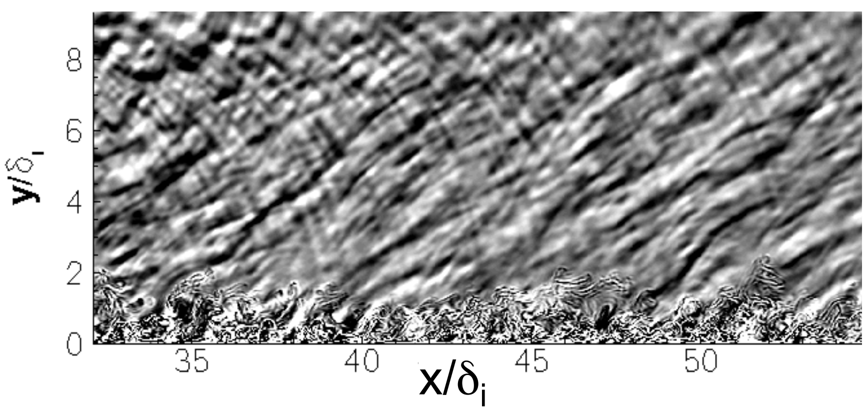
$M_\infty = 14$, $Re_\theta \approx 9540$, $Re_\tau \approx 461$, $T_w/T_r \approx 0.18$

Freestream Disturbance Field

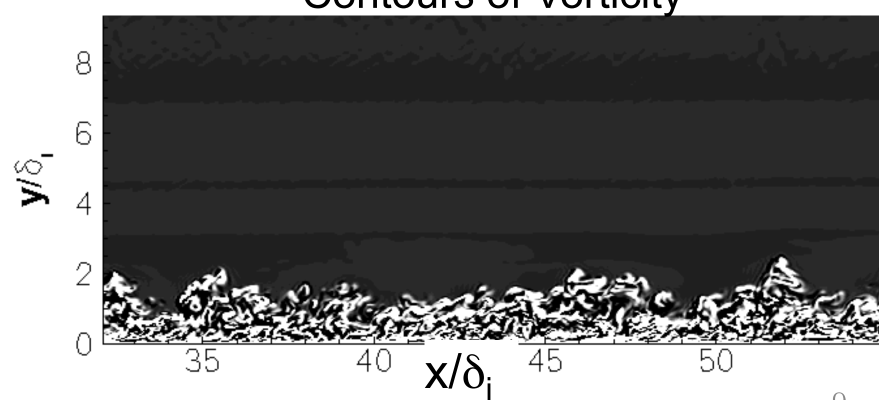
Case	T_w/T_r	$u'_{rms}/\bar{u}$	$v'_{rms}/\bar{u}$	$w'_{rms}/\bar{u}$	$p'_{rms}/\bar{p}$	$\rho'_{rms}/\bar{\rho}$	$T'_{rms}/\bar{T}$
M 2.5	1.0	0.00076	0.0005	0.0008	0.004	0.0028	0.0011
M6Tw025	0.25	0.0025	0.0016	0.0033	0.035	0.025	0.010
M6Tw076	0.76	0.0013	0.0010	0.0021	0.020	0.015	0.0059
M 14	0.18	0.0016	0.0015	0.0028	0.065	0.046	0.0185

- Freestream disturbance field is **acoustic** in nature
  - Small amplitude $\quad p'_{rms}/\bar{p} \approx \gamma(\rho'_{rms}/\bar{\rho})$
  - Isentropic conditions hold
  - Sound mode >> vorticity mode $\quad \left(\overline{\theta'\theta'}/\overline{\omega'_i\omega'_i}\right)_\infty > 1000$

Contours of Dilatation



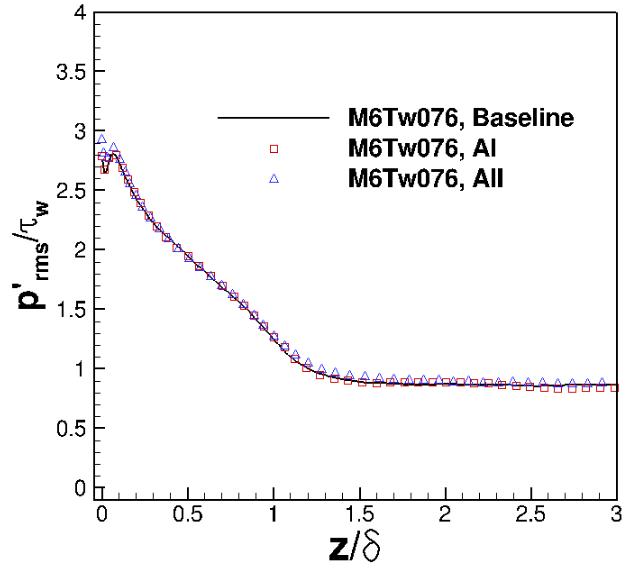
Contours of Vorticity

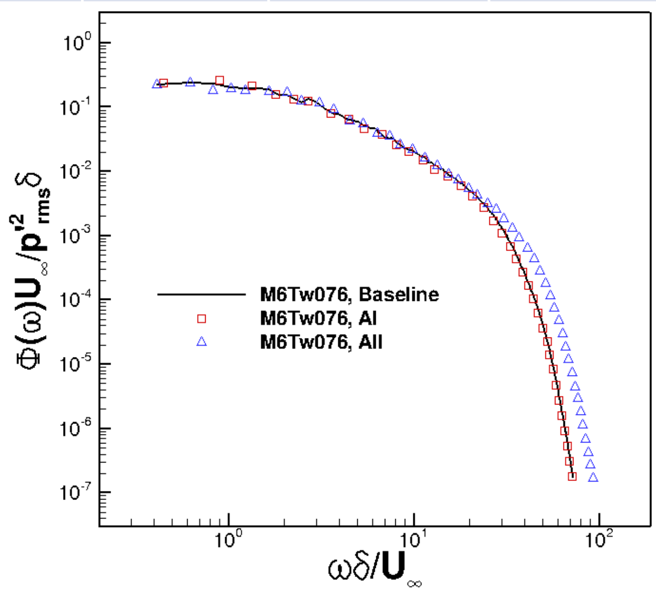


Domain/Grid Sensitivity Assessment

Case M6Tw076

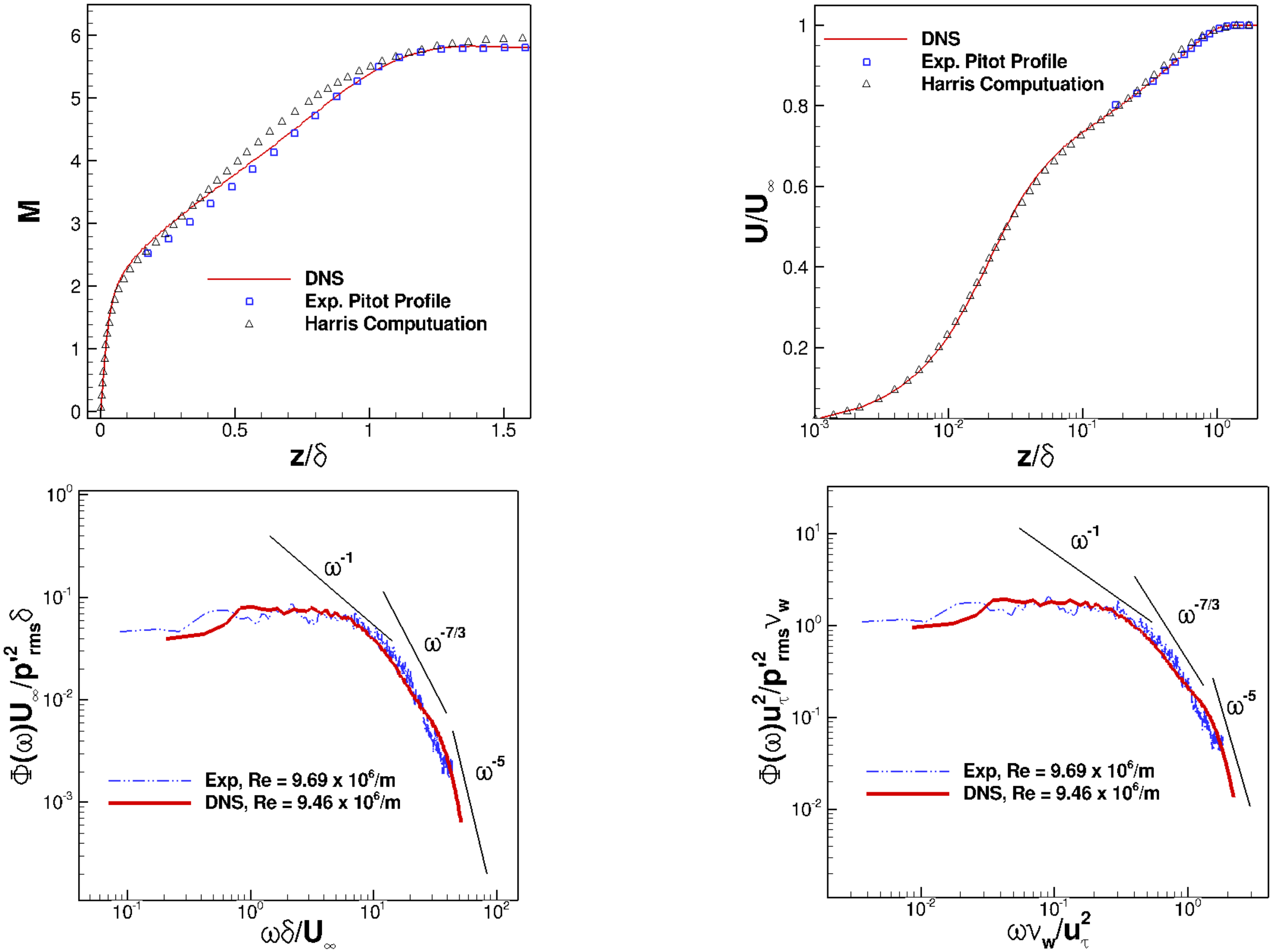
Case	$N_x \times N_y \times N_z$	L_x/δ_i	L_y/δ_i	L_z/δ_i	Δx^+	Δy^+	$(\Delta z^+)_{min}$	$(\Delta z^+)_{max}$
Baseline	1600 × 800×500	58.7	15.7	39.7	9.64	5.14	0.51	5.33
AI	1920 × 320×500	70.4	6.26	39.7	9.64	5.14	0.51	5.33
AII	2400 × 480×500	58.7	6.26	39.7	6.43	3.43	0.51	3.55





Good agreement is achieved up to $\omega\delta/U_\infty \approx 25$ or $\omega\nu_w/u_\tau^2 \approx 1$

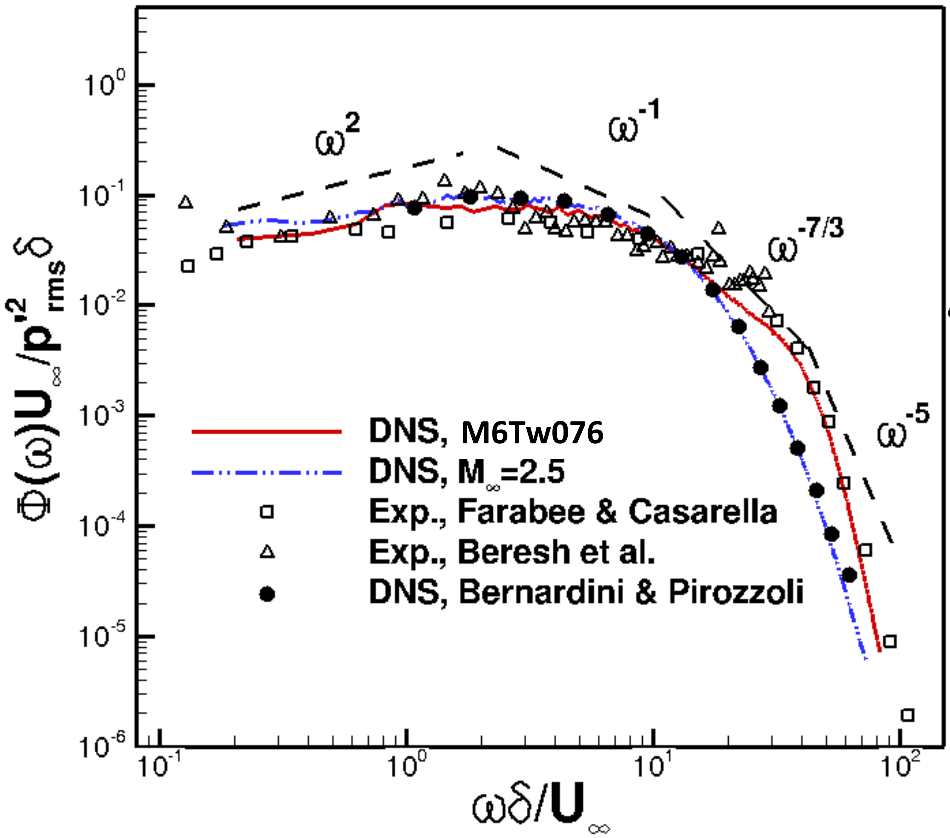
Comparison with Experiment (M6Tw076)



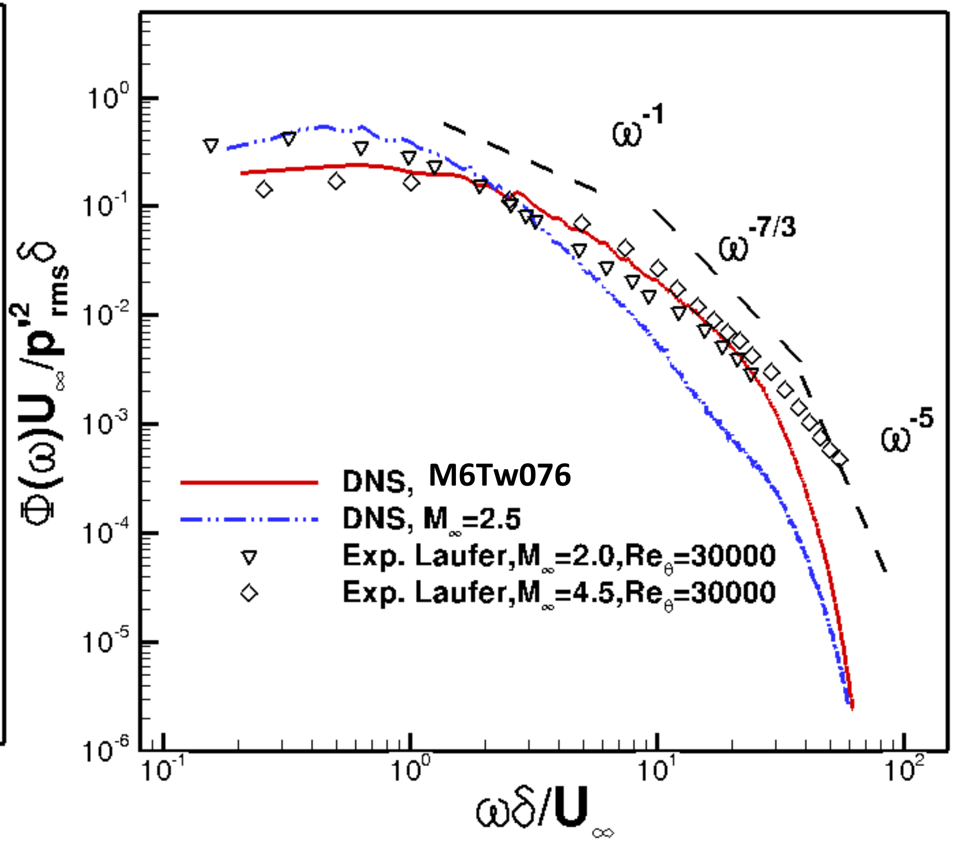
Mean flow predictions and **wall-p'** frequency spectrum are in good agreement with the measurements in the Boeing/AFOSR Mach 6 Quiet Tunnel under noisy condition

Normalized Frequency Spectra

Wall p’

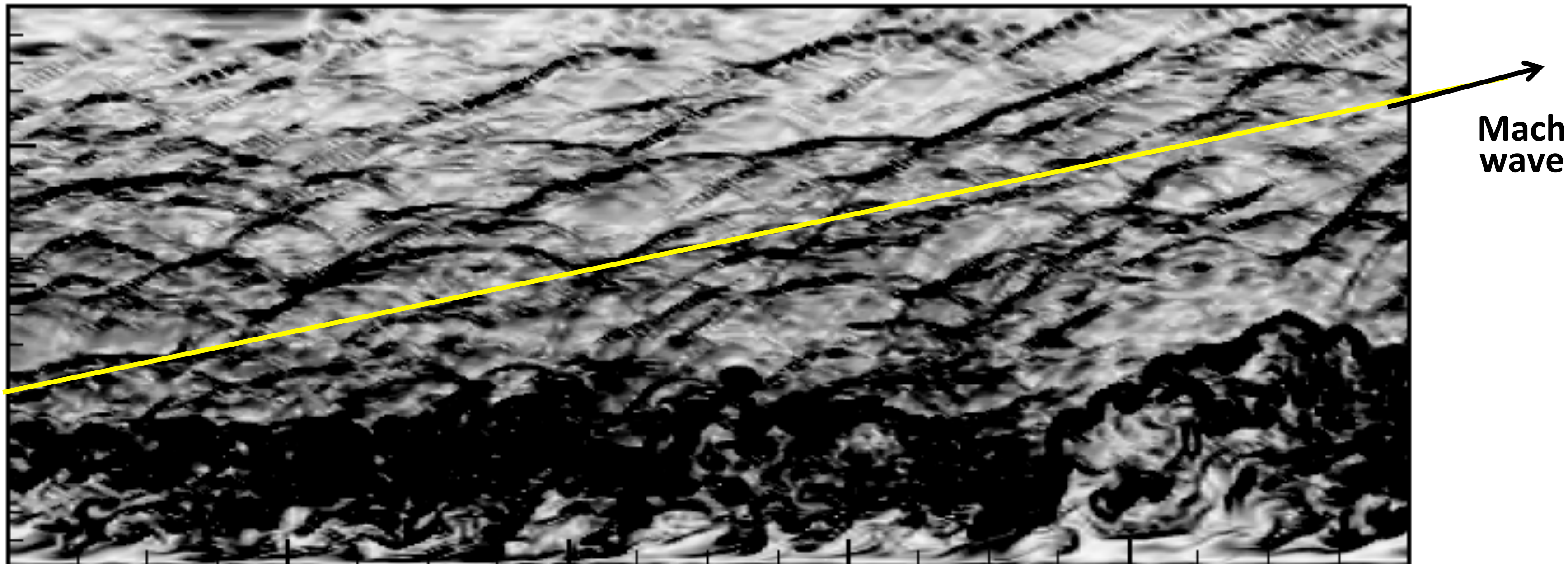


Freestream p’



Numerical Schlieren Visualization

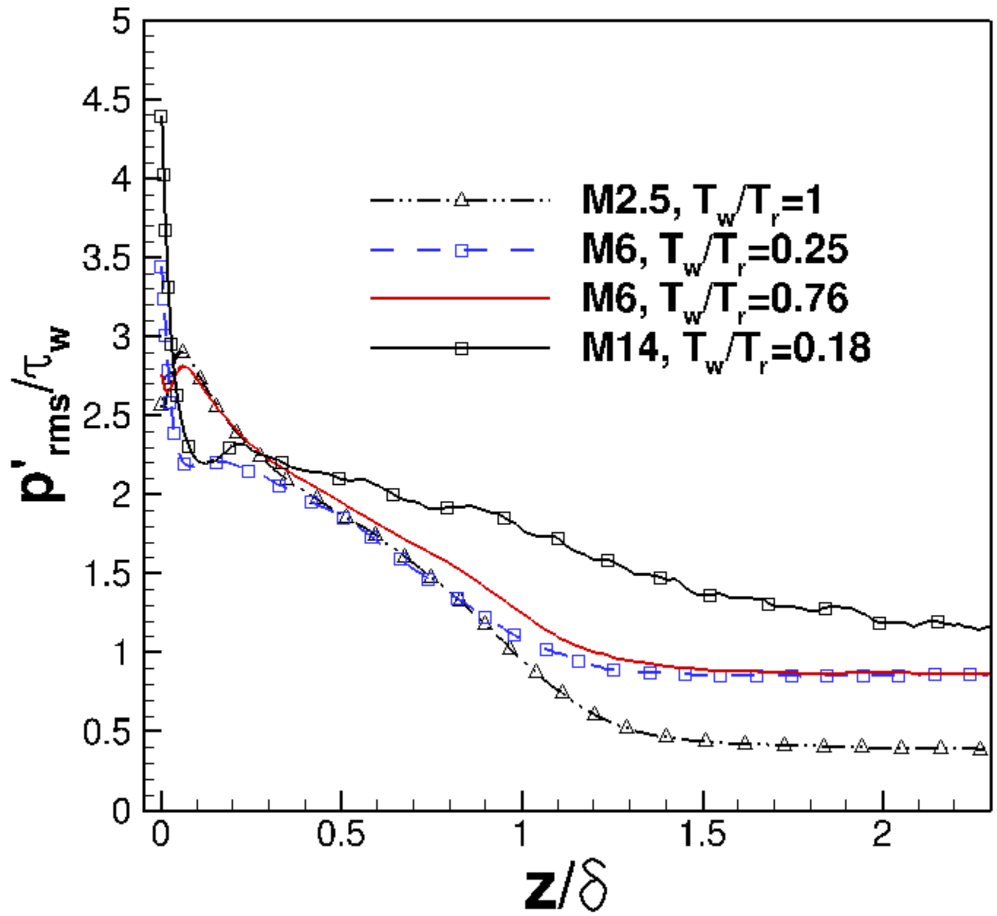
M14Tw18



- Random
- Finite spatial coherence
- Preferred range of orientation for eddy Mach waves
  - Higher inclination than Mach wave direction

Effects of **Freestream Mach number** and **Wall temperature** on Free-stream p' fluctuations

Pressure Fluctuation Intensity

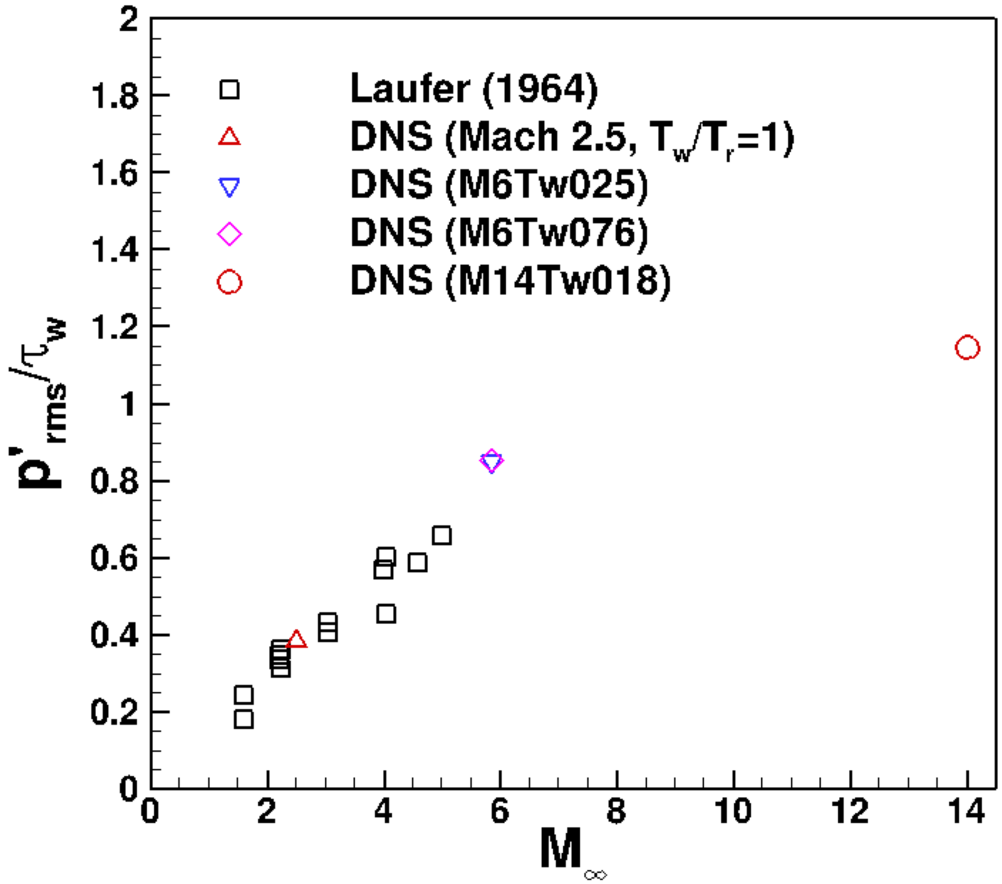


p'_{rms}/τ_w near the **wall** shows a strong wall-temperature dependence

p'_{rms}/τ_w in the **free stream** increases with Mach number and is insensitive to wall temperature

Pressure Fluctuation Intensity

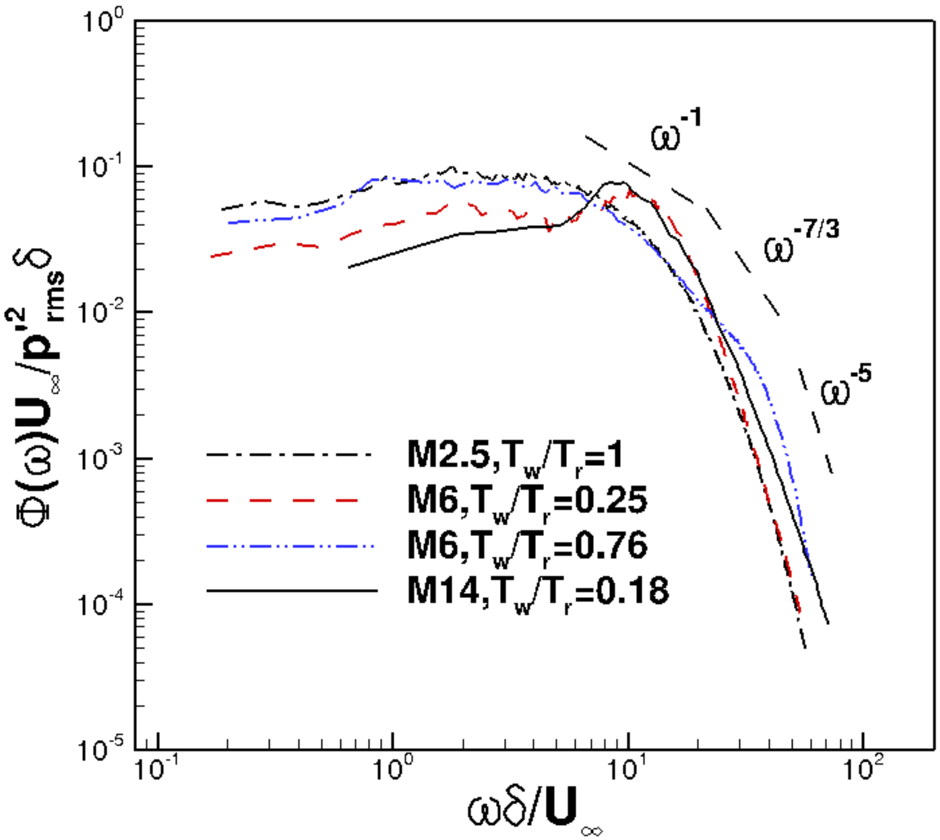
Free stream



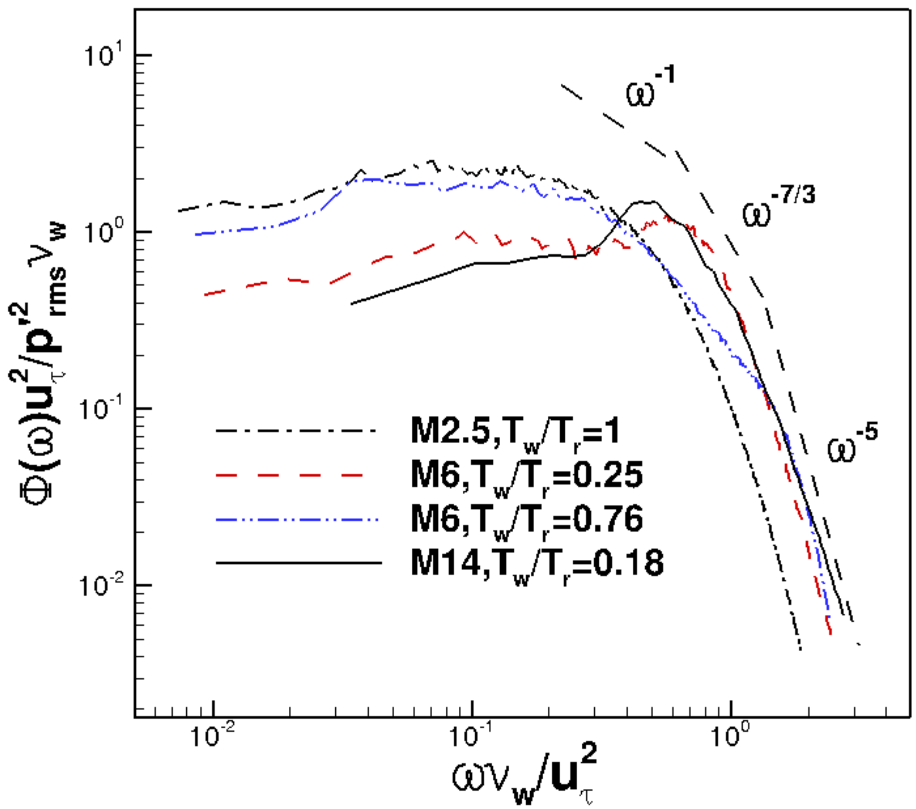
p'_{rms}/τ_w in the free stream shows a strong Mach-number dependence, but is insensitive to wall temperature

Wall p' Frequency Spectra

Outer scale

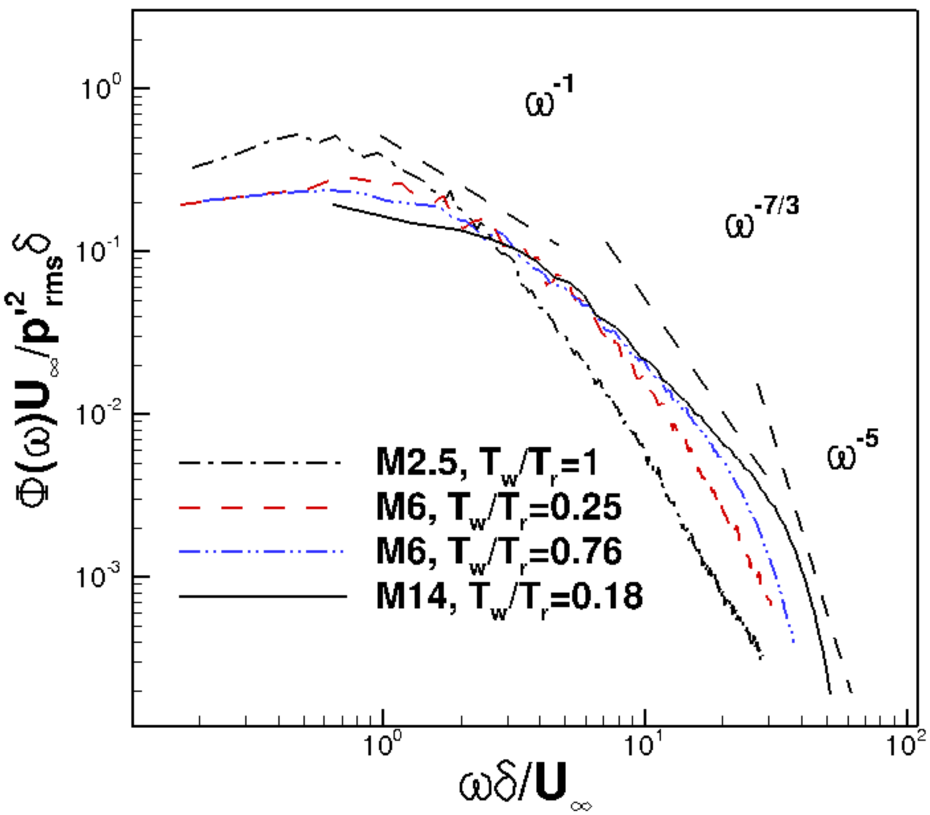


Inner scale

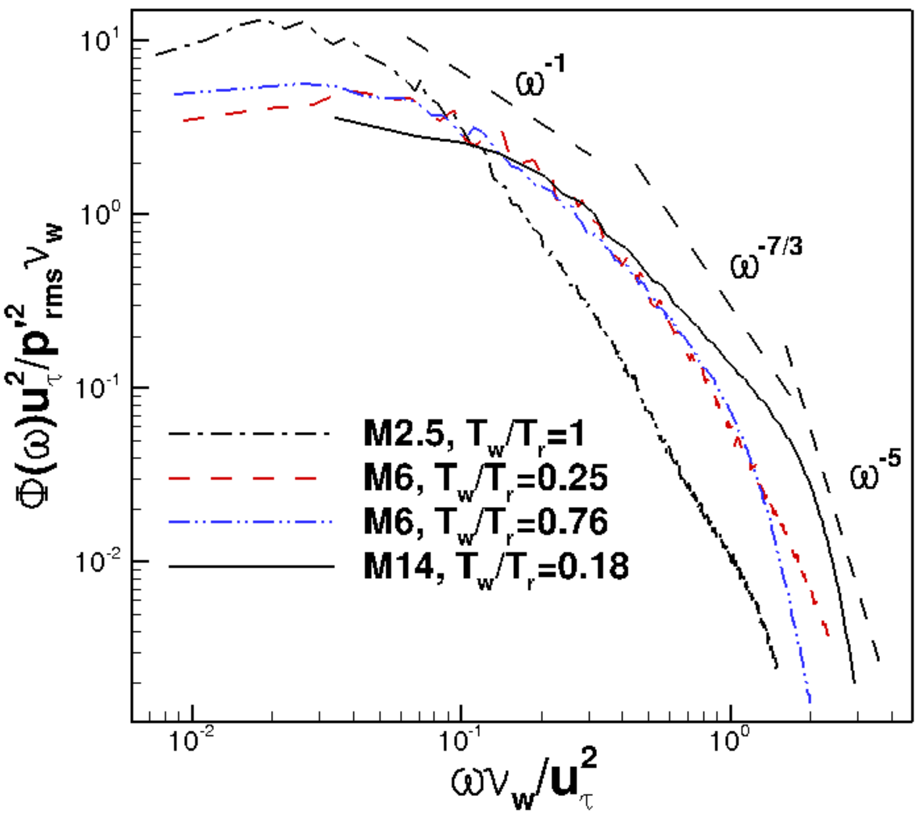


Freestream p' Frequency Spectra

Outer scale

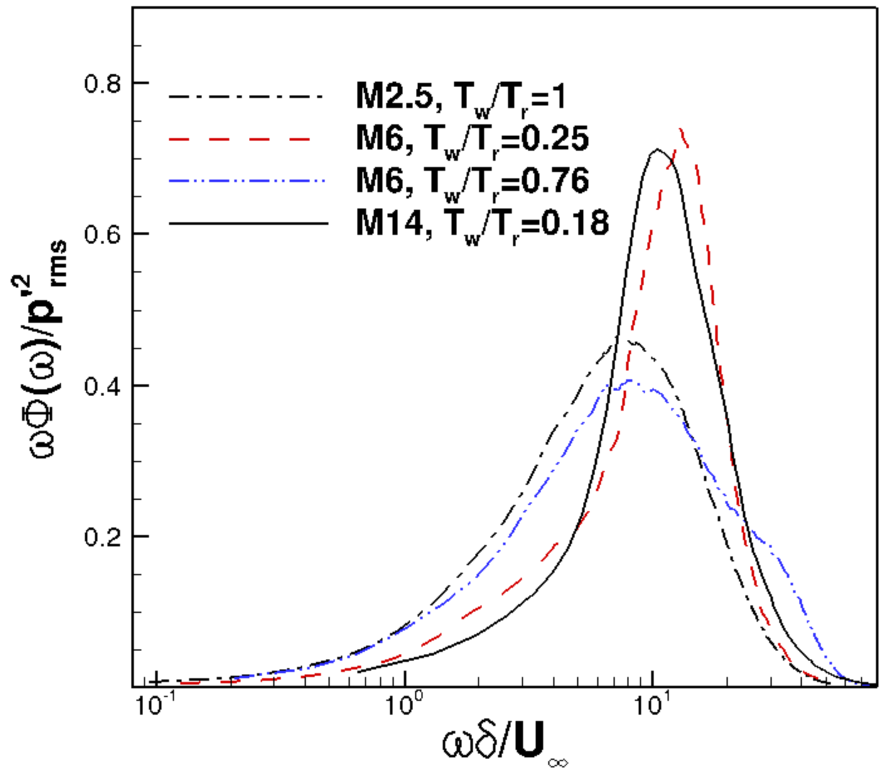


Inner scale

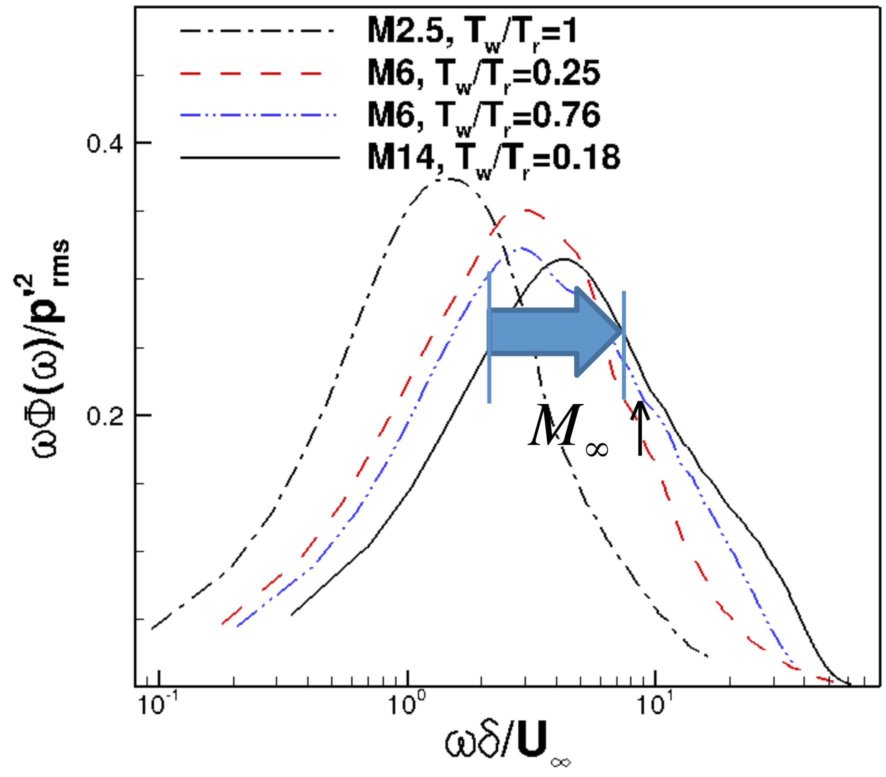


Pre-multiplied p' Frequency Spectra

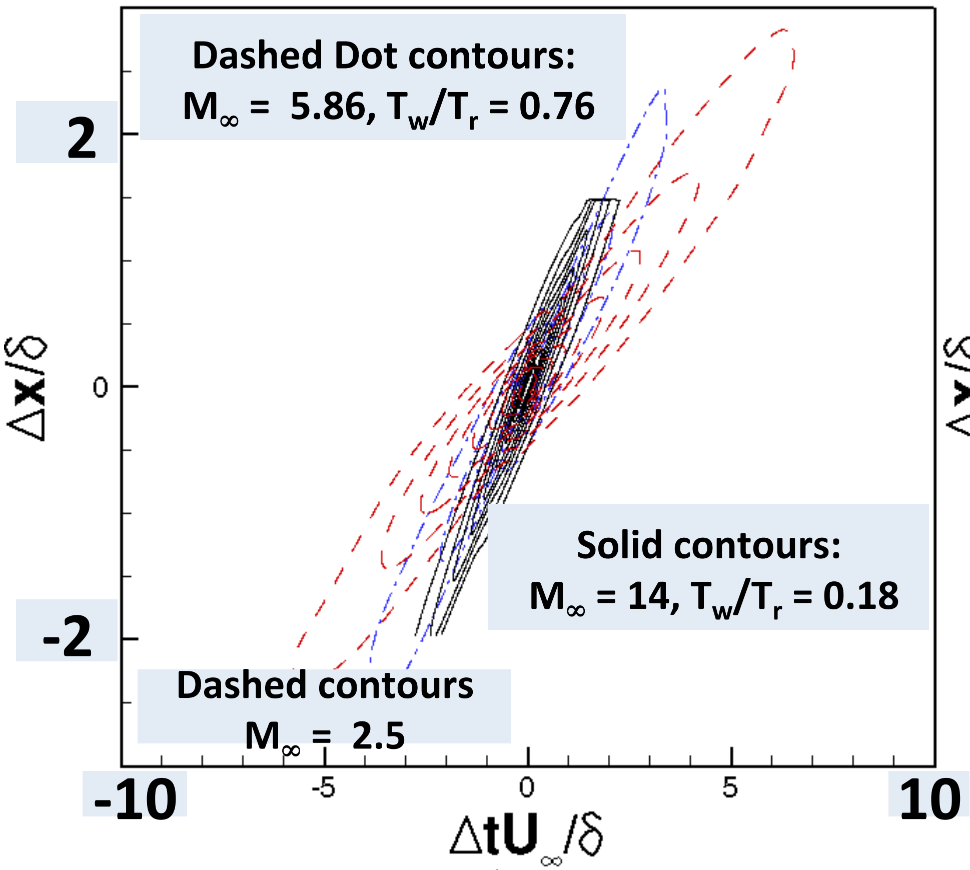
Wall

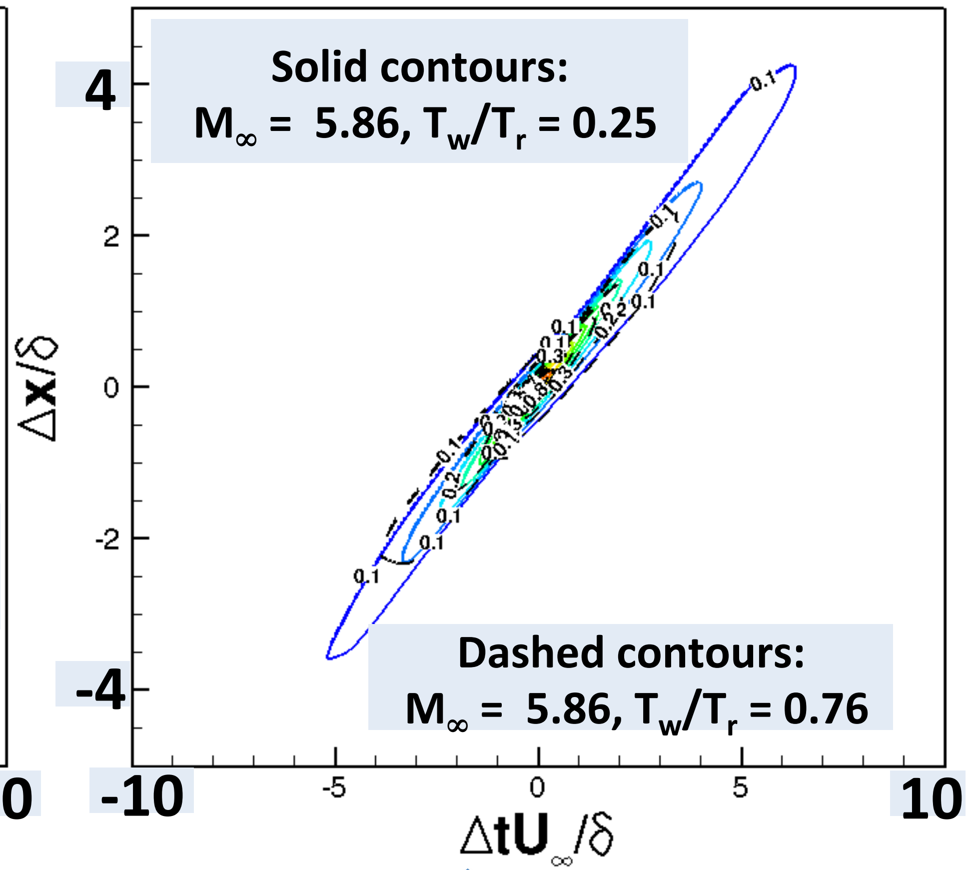


Free stream



Propagation Speed of Acoustic Disturbance

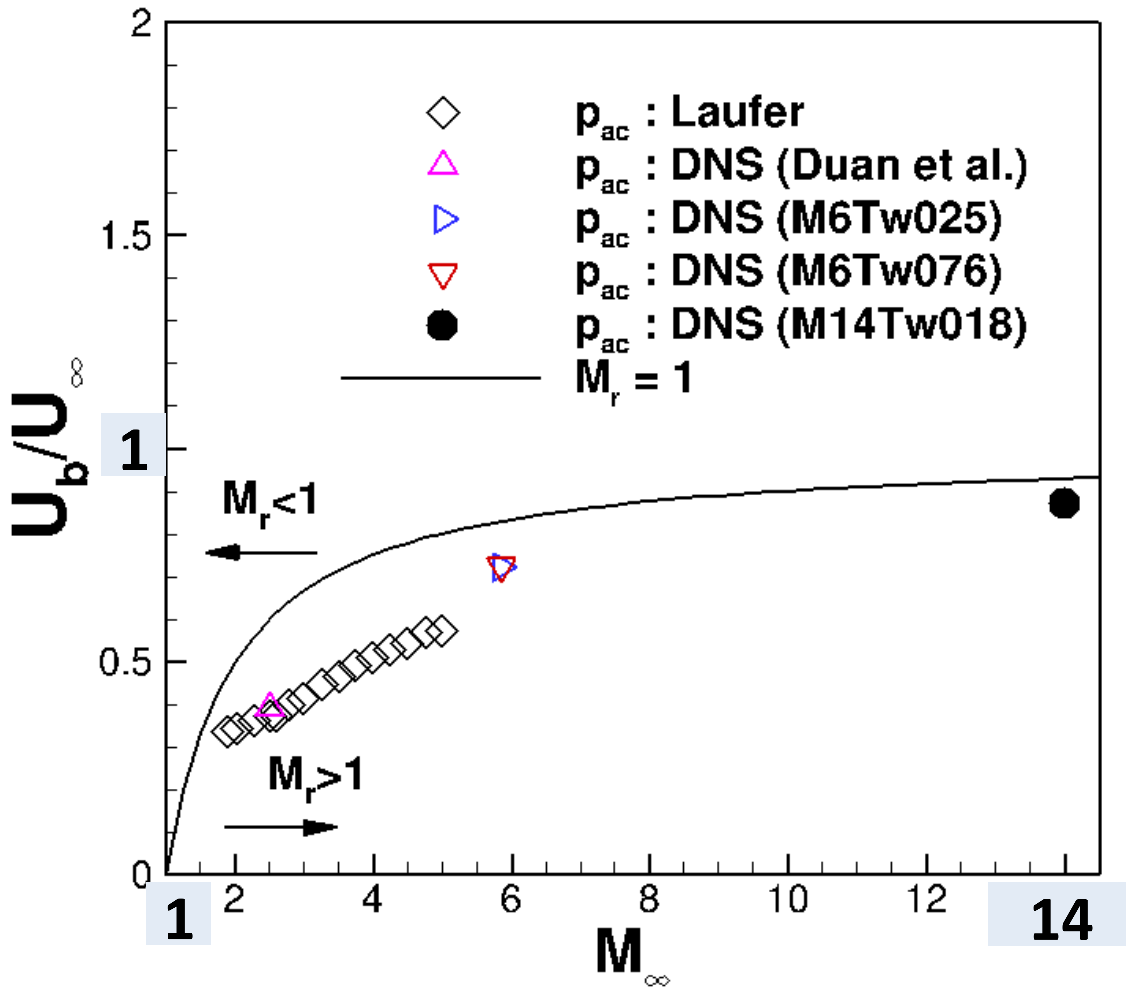




Faster propagation speed of freestream fluctuations as Mach number increases

Wall Temperature has subtle influence on the propagation speed of freestream fluctuations

Propagation Speed of Acoustic Disturbance



$M_r=(U_\infty-U_b)/a_\infty>1$
Consistent with 'Mach-wave radiation' concept

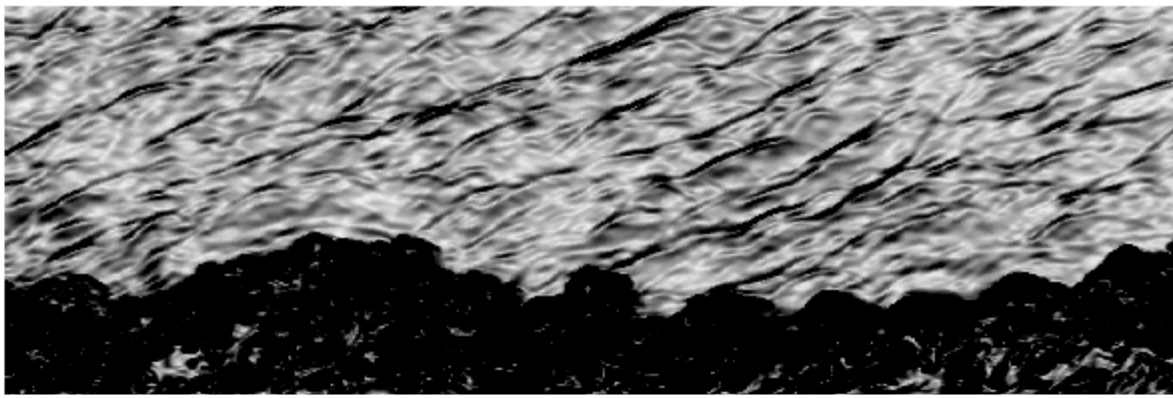
Wall Temperature has subtle influence on the propagation of freestream fluctuations

Preferred Orientation of Eddy Mach Waves

θ: Wave angle

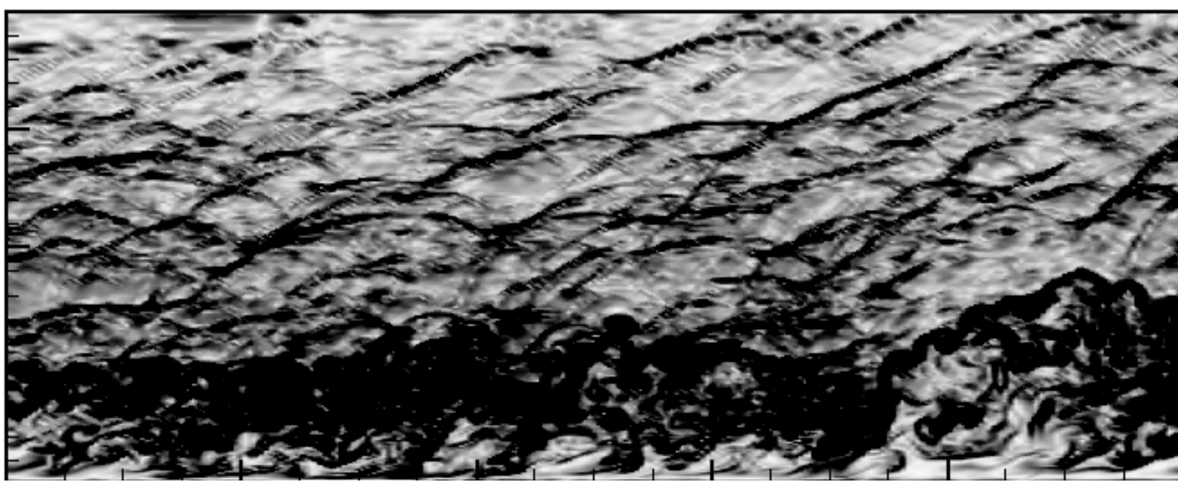
$$\frac{U_b}{U_\infty} = 1 - \frac{1}{M_\infty \sin\theta}$$

θ=30 Deg



M_∞ = 5.86, T_w/T_r = 0.76 (Purdue Quiet Tunnel, noisy run)

θ=28 Deg



M_∞ = 14, T_w/T_r = 0.18 (AEDC Tunnel 9)

Summary and Conclusion

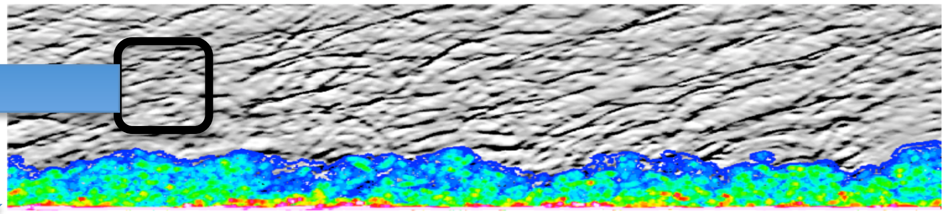
- Freestream acoustic radiation due to (nominally) high-speed turbulent boundary layers was investigated using DNS
  - $M_\infty = 2.5$, $Re_\tau \approx 510$, $T_w/T_r = 1.0$
  - $M_\infty = 5.86$, $Re_\tau \approx 465$, $T_w/T_r = 0.25, 0.76$ (Purdue Quiet Tunnel, noisy run)
  - $M_\infty = 14$, $Re_\tau \approx 461$, $T_w/T_r = 0.18$ (AEDC Tunnel 9)
- Simulation results (mean flow prediction, wall p' frequency spectrum) in good agreement with existing data in literature
- Effects of M_∞ and T_w on freestream p'
  - Strong Mach number dependence

$$M_\infty \uparrow \;\Rightarrow\; p'_{rms}/\tau_w \uparrow, \quad \theta \text{ (wave orientation)} \downarrow, \quad U_b/U_\infty \uparrow$$

  - Appears to be relatively insensitive to T_w (including p'/τ_w, U_b/U_∞, θ)
- Computations provide additional details of the **anisotropic random** field that will be useful for modeling receptivity in conventional tunnels

Outlook

Facility Disturbance + Receptivity



Freestream acoustic disturbances radiated from tunnel-wall turbulent boundary layers

Stochastic Acoustic disturbance field

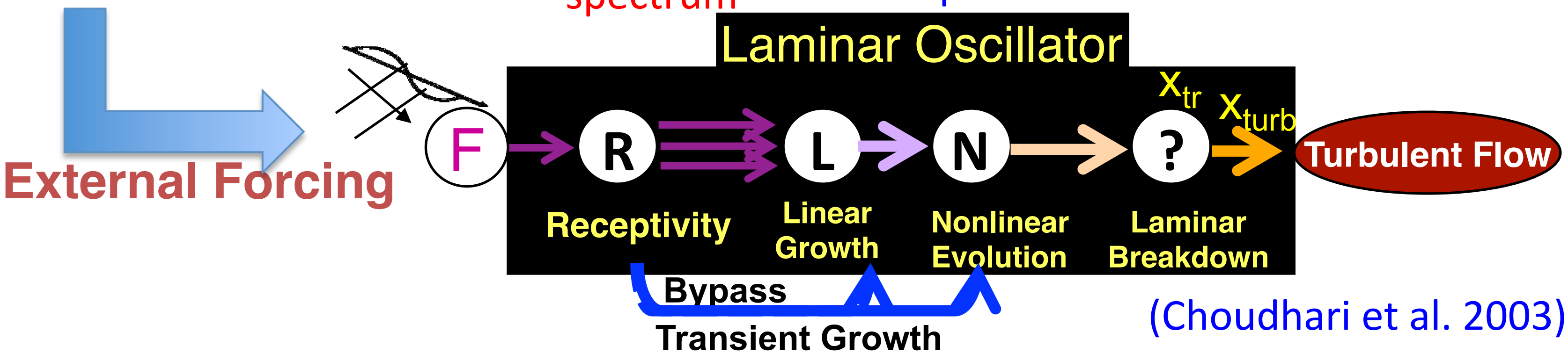
stochastic variables (U_c, θ, ϕ, ω, etc)

$$\begin{Bmatrix} u' \\ v' \\ w' \\ p' \end{Bmatrix} = \mathrm{Exp}\left[\, -i\omega t - i\omega/U_c \,\{x + \tan(\theta)\, z \pm \tan(\phi)\, y\}\,\right]$$

Frequency spectrum

Propagation Speed

Inclination angle



(Choudhari et al. 2003)

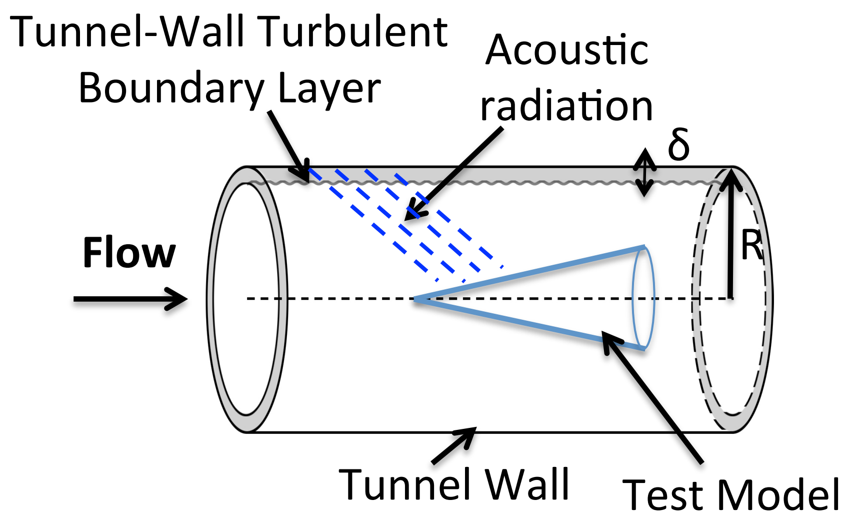
Provide "practical" input data regarding **disturbance environment** for conducting stability analysis in the context of actual wind-tunnel experiments

Enable holistic prediction of transition in High-Speed Boundary Layers

Outlook

Facility Disturbance + Receptivity

Mimic the transition process in the tunnel-like environment



Ongoing collaborations with NATO STO AVT-240 group on Hypersonic Boundary-Layer Transition Prediction

- experimental and numerical studies on the second-mode wave of 7° sharp cone at zero angle of attack

Potential contributions:

- Generate improved knowledge of receptivity process in facility-disturbance environment
- Investigate differences between receptivity to natural broadband disturbance and monochromatic plane-wave disturbances
- provide the initial disturbances in hypersonic boundary layers required for conducting stability analysis.

Acknowledgment

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  - For providing wind-tunnel measurements for comparison with DNS
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